Electromagnetic Telemetry Actuated Firing System for Well Perforating Gun

Inventor: John Hales
Brian Duea
Rebecca McConnell

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ELECTROMAGNETIC TELEMETRY ACTUATED FIRING SYSTEM FOR WELL PERFORATING GUN

BACKGROUND OF THE INVENTION

The present invention generally relates to control of downhole well tools and, in a preferred embodiment thereof, more particularly relates to an electromagnetic telemetry actuated firing system for a well perforating gun.

In a typical construction of a subterranean well, a metal-cased wellbore is extended downwardly through the earth and through a fluid-bearing formation beneath the earth's surface. To operatively communicate the formation with the interior of the casing, for subsequent delivery of formation fluid to the surface, perforations are formed through the casing and outwardly into the formation using a perforating gun structure which is lowered through the casing, typically on a tubing string, to the level of the subterranean formation.

A firing head portion of the lowered perforating gun structure is subsequently actuated to fire the gun and create the desired casing perforations. Perforating gun firing heads are customarily of either a mechanically actuatable or electrically actuatable construction. A mechanical firing head is typically actuated by pressure, or a mechanical device dropped down the tubing to depress a plunger portion of the firing head and thereby initiate firing of the gun. An electrical firing head is typically actuated by an electrical current supplied to a blasting cap

attached to the head to detonate the gun charges. Evolving wellbore technologies and completion techniques have surpassed the ability of current tubing conveyed perforating firing systems to fire their guns by the use of pressure or mechanical means. Moreover, due of such evolving wellbore technologies, a variety of wells simply cannot be perforated using conventional techniques.

For the foregoing reasons it can readily be seen that a need exists for improved apparatus and methods for firing perforating guns that eliminate or at least substantially reduce the above-noted problems, limitations and disadvantages typically associated with conventional perforating gun firing apparatus and methods.

SUMMARY OF THE INVENTION

In carrying out principles of the present invention, in accordance with a preferred embodiment thereof, a specially designed well tool assembly is provided for operative placement in a subterranean wellbore, the well tool assembly representatively being a remotely actuatable mechanical perforating gun assembly operable to form perforations in a metal casing portion of the wellbore.

The perforating gun assembly, when disposed downhole, is selectively operable by an electromagnetic telemetry actuated firing system that includes a surface-disposed transmitter operable to propagate electromagnetic waves through a portion of the earth exteriorly adjacent the wellbore casing. Preferably, the electromagnetic waves are modulated square sine or cosine waves having a frequency in the range of from about 15 Hz or less, and have a predetermined firing address encoded therein.

The perforating assembly illustratively includes a perforating gun having a mechanically actuatable firing head, an actuating section

connected to the firing head and having a motor portion operable to mechanically actuate the firing head, and a receiver operable to detect the electromagnetic waves and responsively operate the motor. The perforating gun assembly may also have a sensor portion for sensing a selected downhole parameter, and a transmitter for propagating through the earth electromagnetic waves indicative of the value of the sensed downhole parameter. These waves may be detected by a suitable surface-disposed receiver.

While the well tool assembly is representatively a perforating gun assembly, other types of well tool assemblies may be utilized if desired and actuated using the electromagnetic telemetry actuating system of the present invention.

According to one aspect of the invention, the tool assembly receiver has a control circuitry portion, and the tool assembly has first and second electrically conductive paths which are insulatively isolated from one another and are respectively operative to transmit an electromagnetic wave signal from a first casing portion to the receiver control circuitry portion with respect to a ground reference from a second casing portion, spaced apart a substantial distance in a downhole portion from the first casing portion, to the control circuitry portion. The receiver control circuitry portion representatively has programmed therein a wave frequency value and a firing address which must be matched with the frequency and firing address of the detected electromagnetic before the circuitry is operative to fire the perforating gun.

Illustratively, the well tool assembly has an elongated, electrically conductive tubular outer body portion and a generally coaxially extending electrically conductive tubular inner body portion, each of the outer and inner body portions having insulative gaps formed therein between

adjacent longitudinal sections thereof. Preferably, the adjacent longitudinal sections of the tubular outer body portion has axially spaced apart threaded end portions threadedly connected to an annular collar member at thread joints containing an electrically insulative material defining spaced apart insulation gaps between the longitudinal sections of the outer body portions and electrically isolating them from one another.

According to another feature of the invention, the receiver has a circuit board portion with a main CPU portion adapted to receive an electromagnetic wave detection signal and a ground reference and responsively generate an actuation request signal, and an auxiliary fail-safe CPU portion operative to receive the actuation request signal, monitor selected parameters of the well tool assembly to detect whether system errors exist, and responsively generate a final actuation signal, to actuate the tool portion of the assembly, only in the absence of sensed system errors.

The perforating gun assembly may be operatively supported in the wellbore on a variety of support structures including a tubing string, coil tubing, wire line, slick line or a casing hanger. The electromagnetic telemetry actuated firing system of the present invention provides a variety of advantages over conventional perforating gun firing systems. For example, the system is essentially wireless, with no downhole cabling required.

The motor section of the well tool may have an output member which is translatable in a selectively variable direction through a selectively adjustable stroke. Additionally, the overall well tool assembly may comprise a plurality of separately actuatable well tools which may be actuated in any desired sequence.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic cross-sectional view through a portion of a subterranean well having disposed therein a perforating gun assembly with which is operatively associated a specially designed electromagnetic telemetry actuated firing system embodying principles of the present invention;

FIG. 2 is a schematic depiction of a preferred electromagnetic wave pattern transmitted through the earth to a receiver portion of the perforating gun assembly;

FIGS. 3A and 3B are enlarged scale schematic cross-sectional views, partly in elevation, through vertically successive portions of the overall perforating gun assembly;

FIG. 4 is a schematic block diagram of a portion of a dual processor circuit board used in an electromagnetic frequency receiver portion of the perforating gun assembly;

FIG. 5 is a schematic side elevational view of an alternate embodiment of the perforating gun assembly; and

FIG. 6 is a schematic side elevational view of a multiple perforating gun assembly.

DETAILED DESCRIPTION

Schematically depicted in cross-sectional form in FIG. 1 is a portion of a well 10 including a wellbore 12 extending downwardly from the surface 14 of the earth 16 through a subterranean hydrocarbon fluid-containing formation 18. Wellbore 12 is lined with a tubular metal casing 20 which is cemented into the wellbore 12, as at 22, and is associated at its upper end with a wellhead portion 24 of a drilling rig 26 at the surface 14. A tubing string 28 extends downwardly from the wellhead 24 centrally through the

casing 20 and forms with the casing 20 an annulus 32 that circumscribes the tubing string 28.

Supported on a lower end portion of the tubing string 28 is a well tool assembly that embodies principles of the present invention and is representatively a perforating gun assembly 34. From top to bottom as viewed in FIG. 1, the perforating gun assembly 34 includes an electromagnetic frequency receiver 36, an electrically operable motor control section 38, a mechanically actuatable firing head 40, and a perforating gun 42, each of which has a generally tubular configuration. The firing head 40 and the perforation gun 42 together form an actuatable well tool.

The perforating gun assembly 34 is operatively positioned within the casing by lowering the assembly 34 through the casing 20 on the tubing string 28 until, as shown in FIG. 1, the perforating gun 42 is positioned in the subterranean formation 18. An optional packer 44 is then set in the annulus 32 above the positioned assembly 34 to seal off a portion of the annulus 32 below the packer 44 from the portion of the annulus 32 above the packer 44.

Still referring to FIG. 1, well 10 also includes a surface-disposed electromagnetic wave transmitter 46 having a positive electrical lead 48 connected to an upper end portion of the metal casing 20, and a negative or grounding electrical lead 50 coupled to the earth 16, representatively via a metal grounding stake 52. When it is desired to fire the perforating gun 42, the transmitter 46 is operated to transmit through the earth 16 electromagnetic waves 54 which are received by the receiver 36. In a manner subsequently described in greater detail herein, in response to detecting the waves 54 the receiver 36 transmits an electrical firing signal to the electric motor control section 38. Motor section 38, in response to

the receipt of the electrical firing signal from the receiver 36, then mechanically actuates the mechanically actuatable firing head 40 which, in turn, fires the perforating gun 42 to create casing perforations 56 that extend outwardly through the casing 20 and the cement 22 and communicate the formation 18 with the interior of the casing 20.

At this point it should be noted that the present invention permits a mechanically actuatable downhole well tool assembly (representatively the gun assembly 34) to be selectively actuated using electromagnetic waves transmitted through the earth. Accordingly, the portion of the tubing string 28 above the receiver is used only to lower and support the assembly 34 - this portion of the tubing 28 is not needed to receive and guide a dropped mechanical firing member to the firing head 40 to transmit a pressure signal to the firing head 40, or to receive and guide a lowered electrical line to electrically actuate the firing head 40. This feature of the invention permits the gun assembly 34 to be lowered through the casing 20, and operatively supported therein, in a variety of other manners not utilizing a tubing string extending to the surface 14. Examples of alternate lowering and support structures include, for example, wire line, slick line, coil tubing, drill pipe, or a casing hanger structure for supporting the lowered assembly.

As previously mentioned, principles of the present invention are not limited to the illustrated perforating gun assembly 34 - such principles could also be advantageously employed with a variety of other types of actuatable downhole well tools. Also, while the illustrated perforating gun 42 is mechanically actuatable via its firing head 40 as later described herein, principles of the present invention could also be advantageously utilized in conjunction with electrically actuatable downhole well tools.

With reference now to FIGS. 1 and 2, the electromagnetic waves 54 propagated through the earth 16 by the transmitter 46 are preferably modulated square sine or cosine waves (see FIG. 2) of the QPSK (quadrature phase shift keying) pulse type which desirably increases the power of the waves and correspondingly increases the maximum earth depth through which they may be effectively transmitted. For purposes later described herein, a predetermined firing address A is suitably encoded in the electromagnetic waves 54 as schematically indicated in FIG. 2. Preferably, the frequency of the electromagnetic waves 54 propagated through the earth 16 by the transmitter 46 is variable within the ULF/ELF frequency range of about 15 Hz or less.

Turning now to FIGS. 3A and 3B, the mechanically actuatable firing head 40 and the perforating gun 42 are of metal, electrically conductive constructions as are tubular outer metal body portions 58,60 of the assembly 36. These body portions 58,60 are representatively defined by lower sections of the metal tubing string 28. As illustrated in FIG. 3A, a lower end 61 of an upper section of the body portion 58 is upwardly spaced apart from the upper end 62 of a lower section of the body portion 58.. These spaced apart end portions 61 and 62 are externally threaded and are threaded into an internally threaded annular metal connection collar 64. For purposes later described herein, a suitable electrically insulative material 66 is disposed in the mated thread areas of the collar 64 and the spaced apart body end portions 61,62 and serves to form dual insulating gaps 66-66 between the body end portions 61,62 and thereby prevent electrical conductance therebetween.

As schematically depicted in FIG. 3A, the specially designed receiver 36 has a cylindrical, electrically conductive interior portion centrally extending through the outer housing 58 and extending upwardly into the

lower end of the tubing string 28, such interior portion including an upper battery section 68 and a lower receiver control section 70 having a circuit board 72 operatively disposed within its interior. Sections 68,70 are electrically coupled by a connector structure 74 interposed therebetween. The upper end of the battery section 68 has secured thereto an electrically conductive centralizer structure 76 with flexible metal arm portions 78 that slidably engage an interior side surface of an outer body portion 58a horizontally facing a corresponding section 20a of the casing.

An upper end portion of the circuit board 72 is electrically coupled to an outer wall portion of the receiver control section 70 by an electrical lead 80, and a lower end portion of the circuit board 72 is coupled to an electrical connector 82 by electrical leads 84 and 86, lead 84 being a ground lead and lead 86 being a firing signal lead. Electrical leads 88,90 extend downwardly from the connector 82 through a central passage portion 92 of the receiver control section 70, with leads 88,90 being respectively coupled to the leads 84,86 through the connector 82.

Turning now to FIG. 3B, the motor control section 38 has a cylindrical, electrically conductive interior portion centrally extending through the outer housing 60 and extending upwardly into the lower end of the outer housing 58, such interior portion including, from top to bottom as viewed in FIG. 3B, a battery section 94, a motor control section 96 and an electric motor 98. For purposes later described herein, a suitable electrically insulative material 100 is suitably interposed between adjacent end portions of the receiver control section 70 and the battery section 94 to form an insulating gap therebetween and preclude electrical conduction between these sections.

Electrical leads 88 and 90 are appropriately routed through the battery section 94, through a central passage 102 therein, and coupled to a

connector 104 disposed at a bottom end portion of the battery section 94. The motor control section 96 has a circuit board 106 disposed therein. The upper end of the circuit board 106 has a ground lead 108 which, via the connector 104, is coupled to the lead 88. The upper end of the circuit board 106 also has an electrical lead 112 which is coupled to the electrical lead 90 via the connector 104. At the bottom end of the circuit board 106 are motor control leads 114 and 116 operatively coupling the circuit board 106 to the electric motor 98. A lower end portion of circuit board 106 is grounded to the housing of motor control section 96 via a suitable grounding path 113.

As schematically depicted in FIG. 3B, the perforating gun 42 contacts a portion 20b of the casing which is in a downwardly spaced apart relationship with the casing portion 20a (see FIG. 3A) adjacent the outer body portion 58a conductively contacted by the centralizer arms 78. Accordingly, during propagation through the earth 16 of the electromagnetic waves 54 by the transmitter 46 (see FIG. 1) the electrical potential at the upper casing section 20a is appreciably higher than at the lower casing section 20b. The previously described dual insulating gaps 66-66 in the outer body portion 58 (see FIG. 3A) and the insulating gap 100 between the receiver control section 70 and the motor control section 96 advantageously permit the simultaneous communication to the receiver circuit board 72 of received, relatively high potential electromagnetic wave signals from the upper casing portion 20a with respect to a relatively low potential ground reference from the lower casing portion 20b through first and second conductive paths which are electrically isolated from one another.

When it is desired to fire the in-place perforating gun 42, the transmitter 46 is activated to propagate the electromagnetic waves 54

through the earth 16, with the waves 54 being propagated at a predetermined frequency, and with the preselected firing address A encoded therein, the frequency and encoded firing address matching a corresponding firing frequency and address pre-programmed into the electronic circuitry of the receiver circuit board 72. Propagated electromagnetic wave signals received at the upper casing section 20a (see FIG. 3A) are transmitted across the casing annulus 32 to the outer body portion 58a and from the outer body portion 58a to the receiver circuit board 72, sequentially via the centralizer 76, outer wall portions of the battery and control sections 68 and 70, and the lead 80, in the form of a wave input signal 118 (see FIG. 4). If desired, a second electrically conductive resilient centralizer (not shown) may be placed between and in conductive contact with the casing section 20a and the outer body portion 58a to facilitate the transmission of electromagnetic wave signals therebetween.

While the electromagnetic waves 54 are being propagated through the earth 16, the lower casing section 20b (see FIG. 3B) is at an appreciably lower electrical potential than the electrical potential of the upper casing section 20a (see FIG. 3A) from which the lower casing section 20b is conductively isolated by the dual insulation gaps 66-66 (see FIG. 3A). This lower (or "ground") potential of the lower casing section 20b is connected to the receiver circuit board 72 (see FIG. 4) as a ground reference 120 (through a conductive path isolated from the conductive path through which the wave input signal 118 reaches the circuit board 72) sequentially via the perforating gun 42 (see FIG. 3B), the firing head 40, body portions of the motor 98, the outer housing of the motor control section 96, the grounding path 113, the motor control circuit board 106, the lead 108, the connector 104, the lead 88, the connector 82 (see FIG. 3A), and the lead 84.

As schematically shown in FIG. 4, the receiver circuit board 72, according to a feature of the present invention, is preferably provided with a main CPU portion 122, which receives the wave input and ground signals 118 and 120, and an auxiliary fail-safe CPU portion 124. If the wave input signal 118 has a frequency and encoded firing address respectively matching the corresponding frequency and firing address programmed into the main CPU 122, the main CPU 122 transmits a firing request signal 126 to the auxiliary fail-safe CPU 124 which verifies the absence of various preselected malfunctions in the overall firing system before responsively transmitting a final electrical firing signal 128 to the motor controller section 96 (see FIG. 3B).

For example, before outputting the final firing signal 128, the auxiliary fail-safe CPU 124 verifies (via power inputs 130,132,134 thereto) that the various voltages in the overall receiver circuitry are at correct levels, and (via reset signals 136,138 transmitted between the two CPU's 122,124) that no defects are present in the various system reset functions. If a system parameter error is detected by the auxiliary fail-safe CPU 124 it will not generate the final firing signal 128, even if the main CPU 122 generates the firing request signal 126.

If the final firing signal 128 is generated by the auxiliary fail-safe CPU 124, the signal 128 is delivered to the motor 98 (see FIG. 3B) sequentially via the lead 86 (see FIG. 3A), the connector 82, the lead 90, the connector 104 (see FIG. 3B), the lead 112, the motor controller circuit board 106, and the leads 114 and 116. Receipt of the final firing signal 128 by the motor 98 causes the motor 98 to upwardly extend a movable rod portion 140 of the motor, as indicated by the arrow 142 in FIG. 3B, in a manner causing the rod 140 to disengage and release an underlying plunger portion 144 of the firing head 40, at the same time allowing wellbore pressure to drive the

plunger. This mechanically actuates the firing head 40 which, in turn and in a conventional manner, fires the perforating gun 42. The motor 98 may be operative to translate the rod 140 in selectively variable directions through a selectively adjustable stroke if desired.

A variety of modifications can be made to the representatively illustrated perforating gun assembly 34 (see FIG. 1), if desired, without departing from general principles of the present invention. For example, the receiver 36, motor control 38 and firing head 40 could be positioned on the bottom end of the perforating gun 42 instead of its top end as schematically depicted in FIG. 1. Further, one or more additional perforating gun assemblies 34 could be utilized within the casing 20 instead of the single perforating gun assembly 34 illustratively shown in FIG. 1. Additionally, the specially designed perforating gun assembly 34 could also be advantageously utilized in conjunction with the transmitter in a subsea well application.

While the depicted perforating gun assembly 34 is representatively designed to operate on a "receive only" basis, it can be easily modified to additionally transmit selected data to the surface if desired. For example, an alternate embodiment 34a of the previously described perforating gun assembly 34 is schematically shown in FIG. 5. For ease in comparing the assembly embodiment 34a to the previously described assembly embodiment 34, elements in the assembly embodiment 34a similar to those in the assembly embodiment 34 have been given the same reference numerals to which the suffixes "a" have been appended.

In the alternate perforating gun assembly embodiment 34a, an electromagnetic frequency transmitter 146 is added to the assembly 34a, representatively between the receiver 36a and the motor section 38a, and is associated with a suitable sensor 148 operative to sense a

predetermined downhole parameter, such as temperature or pressure. The transmitter 146 may be utilized to propagate electromagnetic waves 150 through the earth 16 to a suitable surface receiver 152, the waves 150 having suitable characteristics imparted thereto which are indicative of the sensed downhole parameter.

While a single well tool assembly 34 (representatively a perforating gun assembly) has been illustratively depicted as being operatively positioned within the wellbore 12 (see FIG. 1), a plurality of well tool assemblies, such as the well tool assemblies 34' and 34'' schematically depicted in FIG. 6, may alternatively be supported in the wellbore 12 on, for example, the tubing 28. These well tool assemblies 34' and 34'' may be sequentially actuated, in any predetermined order, in response to their receipt of actuating signals 128',128'' generated by their receiver sections in response to their detections of corresponding electromagnetic waves being propagated through the earth by the transmitter 46. The electromagnetic waves that create these actuating signals 128',128'' have different actuating addresses encoded therein, and may also have different frequencies.

The electromagnetic telemetry actuated firing system representatively described above provides a variety of advantages over conventional perforating gun firing systems. For example, the system is essentially wireless, with no downhole cabling required.

The foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the present invention being limited solely by the appended claims.